EPA Regional Priority AFO Science Question Synthesis Document

Air Emission Characterization and Management

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SECTION 2: AIR EMISSIONS CHARACTERIZATION AND MANAGEMENT

The 2002 U.S. Census of Agriculture reports 400,000 AFOs in the beef, dairy, swine, and poultry sectors. While most of these operations are small, the majority of meat, dairy, and egg production occurs at large AFOs. Over the past two decades, the trend of concentrating food production in large, confined operations combined with an increased geographical concentration of AFOs has heightened public concern about the potential environmental effects of AFO emissions.

This section summarizes our understanding of AFO emissions and potential mitigation techniques. Section 2.1 identifies the substances that are emitted from AFOs, the emission sources, and the factors that influence emissions. Section 2.2 explains the fate of these emissions in the atmosphere. Section 2.3 summarizes the methods for estimating emissions from AFOs and Section 2.4 identifies techniques for reducing AFO emissions.

Emissions from an AFO can be released directly from the animals and as products of manure decomposition. For example, carbon dioxide is emitted directly by respiration and as a product of the microbial decomposition of manure. Similarly, the ruminant digestive process in cattle generates significant methane emissions, as does the decomposition of manure under anaerobic conditions. The discussion in this section focuses on emissions from manure and entrained particulate matter (PM), and excludes consideration of emissions from animal respiration or digestive processes.

2.1 Emissions Associated with AFOs

Animal feeding operations emit PM, ammonia, nitrous oxide, hydrogen sulfide, methane, volatile organic compounds (VOC), hazardous air pollutants (HAP), and carbon dioxide. There are three potential sources of emissions: animal confinement facilities, manure management systems, and manure land application sites. Table 2-1 summarizes the substances that can be emitted from each of these operational components. The following subsections explain the mechanisms responsible for AFO emissions.

2.1.1 Particulate Matter

Particulate matter emissions from AFOs are generated by entrainment of dried manure and other materials (e.g., feed, soil, animal dander, bedding) in the ambient air. Although animal dander and feather particles from poultry are constant constituents, the other components that comprise PM emissions vary. For poultry and swine, feed particles will constitute a significant fraction of PM emissions because the dry, ground feed grains and other ingredients used to formulate these feeds are inherently dusty. For beef and dairy cattle, dry forages or feed grains also generate PM, but most likely to a lesser degree. Fermented feeds (i.e, silage), which have relatively high moisture contents, tend to generate less PM than other types of feed. At feedlots, PM emissions will typically include entrained surface materials (soil and dust) and dried manure.

Due to sorption, PM can serve as a transport mechanism for ammonia, VOC, and hydrogen sulfide.

Particulate matter emissions from AFOs include both PM_{10} and $PM_{2.5}$. However, the relative size fractions of PM_{10} and $PM_{2.5}$ emitted from AFOs have not been well characterized.

Ammonia (along with sulfur dioxide and nitrogen oxides) is one of the major precursors to the secondary formation of $PM_{2.5}$ in the atmosphere. In the ambient air, sulfur dioxide and nitrogen oxides are converted to sulfuric and nitric acids, which then react with ammonia to form ammonium sulfate, ammonium nitrate, and other fine particulates. At this time, EPA has determined that the control of sulfur dioxide and nitrogen oxides generally is the most effective way to reduce secondarily formed sulfate and nitrate particles. States will have the prerogative to control ammonia emissions in locations where control of emissions of sulfur dioxide and nitrogen oxides is inadequate to achieve desired reductions in $PM_{2.5}$ concentrations due to the formation and precipitation of ammonium salts.

2.1.2 Gaseous Compounds

Gaseous compounds are the products of the microbial decomposition of manure. The formation of gases begins immediately at excretion and continues until decomposition is complete. However, emissions generally cease after the manure is incorporated into the soil by injection or tilling. Once in the soil, the components in manure typically are converted microbially to nonvolatile compounds and nutrients that are absorbed by plants. Exceptions are emissions of nitrous oxide and carbon dioxide which continue after manure is incorporated in the soil. The following sections describe the principal gaseous compounds that are emitted from manure degradation.

2.1.2.1 Ammonia

Ammonia (NH_3) is produced as a by-product of the microbial decomposition of the organic nitrogen compounds in manure under both aerobic and anaerobic conditions (Loehr, 1984). Nitrogen compounds in urine (urea from mammals and uric acid from poultry) biodegrade rapidly and are transformed to ammonia soon after excretion. The formation of ammonia continues with the microbial breakdown of the other organic nitrogen compounds in manure. Because ammonia is highly soluble in water, volitalization of ammonia from manure is more rapid when manure is handled as a solid. However, there may be little difference in total ammonia emissions between solid and liquid manure handling systems if liquid manure is stored over extended periods of time prior to land application.

2.1.2.2 Nitrous Oxide

Nitrous oxide (N_2O) is a greenhouse gas that has approximately 310 times the heat trapping capacity of carbon dioxide. It can be produced from the microbial decomposition of organic nitrogen compounds in manure. The formation of nitrous oxide is a 3-step process, beginning with mineralization of organic nitrogen to ammonia followed by nitrification and denitrification. Nitrification is the microbial oxidation of ammonia to nitrites and nitrates, and requires an aerobic environment. Denitrification most commonly is a microbially mediated process where nitrites and nitrates are reduced under anaerobic conditions. The principal end product of denitrification is dinitrogen gas (N_2) (Alexander, 1999). However, small amounts of nitrous oxide as well as nitric oxide (NO) also can be generated under certain conditions. Therefore, for nitrous oxide emissions to occur, the manure must first be subject to aerobic conditions and then anaerobic conditions. An example of this scenario would be dry manure on a feedlot or land application site that becomes saturated by rain. Once in the air, N_2O diffuses to the stratosphere where it can remain for hundreds of years.

2.1.2.3 Hydrogen Sulfide

Hydrogen sulfide (H_2S) is produced as sulfur compounds in manure decompose under anaerobic conditions. Although hydrogen sulfide is the predominant compound, other reduced sulfur compounds (e.g., methyl mercaptan, dimethyl sulfide, dimethyl disulfide, and carbonyl sulfide) are also emitted from manure. There are two primary sources of sulfur in animal manures: (1) sulfur amino acids contained in feeds, and (2) feed additives that contain inorganic sulfur compounds (e.g., copper and zinc sulfates). Although sulfates are used as trace mineral carriers in all sectors of animal agriculture, their use is more extensive in the poultry and swine industries. In some areas, sulfur in drinking water also can be a significant source of sulfur in manures.

2.1.2.4 Methane

Methane (CH_4) is a greenhouse gas that has approximately 21 times the heat trapping capacity of carbon dioxide. Methane is a product of the microbial degradation of organic matter under anaerobic conditions. The formation of methane is a two-step process in which complex organic carbon compounds (e.g., carbohydrates, proteins, and fats) are first reduced to organic acids and other VOC and then further reduced to methane and carbon dioxide (Grady and Lim, 1980; Alexander, 1999). In an anaerobic lagoon, which is designed to optimize the microbial breakdown of volatile solids, the biogas will contain 60 to 70 percent methane, 30 to 40 percent carbon dioxide, and small amounts of VOC. In other types of liquid storage facilities, biogas will contain less methane and more carbon dioxide and VOC. Because methane is essentially insoluble in water, it is emitted immediately following formation.

Manures managed as solids typically will not be significant sources of methane. As manure dries, the reduction in moisture content allows sufficient diffusion of atmospheric oxygen into the manure to preclude anaerobic activity or to permit the subsequent microbial oxidation of any methane formed.

2.1.2.5 Volatile Organic Compounds

Volatile organic compounds are intermediate metabolites formed during the degradation of organic matter in manure. Under aerobic conditions, such as those found in dry manure management facilities, any VOC that are formed are rapidly oxidized to carbon dioxide and water. Under anaerobic conditions, VOC are converted by methanogenic bacteria to methane (Grady and Lim, 1980; Alexander, 1977). If an adequate balance exists between the population of methanogenic bacteria (methanogens) and the bacteria responsible for VOC formation, the potential for VOC emissions is small. Otherwise, VOC will accumulate in the manure and ultimately be volatilized to the air.

Most VOC from AFOs are emitted from manure that is collected and stored as a liquid or semi-solid slurry. The high organic loading rates that are characteristic of liquid and slurry manure storage facilities preclude the establishment of the balanced microbial environment necessary for methane formation. Therefore, VOC emissions are highest at liquid manure storage facilities (e.g., storage tanks, ponds). On the other hand, VOC emissions will be relatively low from properly designed and operated stabilization processes (e.g., anaerobic lagoons). In most cases, VOC emissions will vary seasonally, because the rate of VOC formation, reduction to methane, and volatilization of VOC emissions varies with temperature. Emissions from anaerobic lagoons in cold climates will be relatively low in the winter, peak in the late spring as temperature increases, and then decline throughout the summer as methane production increases. Emissions from manure storage facilities will peak from the late spring through early fall. These seasonal changes have less effect in warmer climates and do not affect VOC emissions in subtropical regions.

The specific VOC emitted will vary depending on temperature-solubility relationships. Although the data regarding speciation of VOC emissions are very limited, one study (O'Neil and Phillips, 1992) identified 168 VOC measured in the air around AFOs. These VOC include alcohols, aldehydes, amines, carboxylic acids, esters, mercaptans, phenolics, and sulphides. Appendix A contains a list of the VOC associated with livestock manure. Some of these compounds have highly objectionable odors and contribute significantly to the odor problems often associated with AFOs.

2.1.2.6 Hazardous Air Pollutants

A small portion of the VOC emitted from manure decomposition at AFOs are HAP. Hazardous air pollutants are those pollutants that are known or suspected to cause cancer or other serious health effects, such as reproductive effects or birth defects. Under Section 112 of the Clean Air Act, 188 air pollutants have been listed as HAP. Although the data regarding speciation of VOC emissions are very limited, one study (O'Neil and Phillips, 1992) identified 21 HAP among a mix of 168 VOC measured in the air around AFOs.

2.1.2.7 Carbon Dioxide

Carbon dioxide, a greenhouse gas, is produced by the microbial degradation of organic matter under both aerobic and anaerobic conditions. Under aerobic conditions, carbon dioxide and water are the end-products, with essentially all of the carbon emitted as carbon dioxide. Under anaerobic conditions, approximately 30 to 40 percent of the organic matter is microbially converted to carbon dioxide with the remainder being converted to VOC and methane. Under these conditions, carbon dioxide is formed as a by-product of the decomposition of complex organic compounds that contain oxygen. Thus, carbon dioxide will be emitted under both aerobic and anaerobic conditions and will occur wherever manure is present. Manure decomposition releases carbon dioxide that was recently fixed when carbon dioxide was utilized by photosynthesis in the production of feedstuffs utilized by AFOs. Therefore, carbon dioxide emissions from AFOs do not contribute to a buildup of greenhouse gases.

2.1.3 Emission Sources

An AFO is comprised of animal confinement facilities, a system for manure management (including handling, storage, and in some cases stabilization), and manure land application sites. Because many different methods of confinement and manure management are available, there is a wide range of AFO configurations. The design and operation of an AFO varies depending on animal type, animal age, regional climatic conditions, and operator preference.

2.1.3.1 Confinement Facilities

A confinement facility may be a totally enclosed structure, a partially enclosed structure, or an open paved or unpaved lot. Table 2-2 describes the most common types of confinement facilities, which vary among and within the animal sectors.

All confinement facilities are potential sources of PM and gaseous substance emissions. However, the composition and magnitude of the emissions depend on how the animals are confined, whether the manure is handled as a solid or liquid, and the frequency of manure removal from the confinement area. Beef are typically confined in open feedlots. Some dairy operations also use feedlot-type confinement facilities. Feedlots can include structures to provide shelter (e.g., shade or shelter from inclement weather). Because they are subject to variable wind direction and speed, open feedlots are intermittent sources of PM. The mass of PM emitted depends on the surface moisture content, wind speed, and degree of animal movement. Therefore, precipitation is an important factor in determining PM emissions from open facilities. The microbial environment at open facilities is predominantly aerobic, although transient anaerobic conditions can exist due to the presence of moisture (e.g., due to poor drainage or heavy precipitation). These anaerobic areas can be sources of hydrogen sulfide, methane, and VOC emissions. Since ammonia is formed under both aerobic and anaerobic conditions, it is also emitted from open facilities.

Poultry, swine, veal calves, and dairy cows are typically confined in partially or totally enclosed facilities for all or part of the year. These facilities use natural or mechanical ventilation to regulate the temperature and humidity. With mechanical ventilation, gases and PM are emitted through the ventilation system when in use. When partially enclosed facilities are naturally ventilated, all building openings are emission points. Enclosed facilities are sources of ammonia since formation of this compound occurs rapidly upon excretion of manure. Where manure is handled as a liquid, enclosed facilities can also be sources of hydrogen sulfide, methane, and VOC emissions due to the presence of anaerobic conditions.

2.1.3.2 Manure Management System

A manure management system is the collection of equipment used to remove manure from the confinement area and to store the manure until ultimate disposal. Components of the manure management system may be integrated into the confinement facility or located adjacent to the confinement facility. Table 2-3 summarizes the manure management systems associated with the most common types of confinement facilities.

In operations where manure is handled as a solid (e.g., beef cattle and broilers), manure is periodically removed from the confinement area. This manure is sometimes applied to land immediately or it may be stored in stockpiles prior to land application. Manure stockpiles may be partially enclosed (e.g., a roof with three side walls), temporarily covered (e.g., polymeric membrane), or uncovered. Some facilities stabilize solid manure by composting. Composting can reduce odors and pathogens if adequate aeration is provided to maximize aerobic activity.

When dairy, veal calf, swine, and poultry manures are managed as a liquid or a semi-solid slurry, storage normally is part of the waste management system. Storage may be in: 1) a tank below a slatted floor within the confinement facility, 2) an above-ground or in-ground tank or earthen pond outside of the confinement facility, or 3) an anaerobic lagoon, which provides stabilization in combination with storage. Stabilization reduces volatile solids, odor, and pathogens. Separation of coarse solids may precede storage, especially with dairy manure.

When manure is stored as a solid, the principal substance emitted is ammonia. However, PM emissions are also possible especially when the stored manure has a very low moisture content and is exposed to wind. When manure is stored as a liquid or a slurry, the principal substances emitted are ammonia, hydrogen sulfide, VOC, and methane.

2.1.3.3 Land Application Site

Currently, almost all livestock and poultry manure is applied to cropland or pastures as a source of nutrients. Solid and semi-solid manure is applied to the soil surface using tractor-drawn or truck-mounted spreaders. Following application, the manure may be incorporated into the soil by a tillage practice such as plowing or disking. Semi-solid manure slurries also can be directly injected into the soil. Typically, liquid manures are applied using sprinkler irrigation systems. Although less common, surface application (with or without incorporation) and direct injection can also be used for liquid manure.

Land application processes emit both PM and gaseous compounds. The mass emitted depends on the form of manure being applied and the method of application. Irrigation of liquid manure will cause the highest emissions of gases (i.e., ammonia, hydrogen sulfide, VOC) due to the increased opportunity for volatilization. Emissions from manure (liquid or solid) that is surface applied and not immediately incorporated into the soil will be higher than when the manure is immediately incorporated by disking or plowing. Injection will produce the lowest gaseous emissions. Particulate matter emissions will occur with dry solid manure disposal, and the magnitude will depend on moisture content of the manure.

Generally, the frequency of emissions from land application sites depends primarily on the method of manure application. When irrigation is used, multiple application events may occur throughout the growing season. Multiple applications also may occur when solid and semi-solid manure is used on land for growing hay and grass silage. When solid and semi-solid manure is used on land for growing row crops (e.g., corn or soybeans), applications are limited to the spring before planting and the fall after harvesting. However, fall manure applications are becoming less common due to impacts on surface and ground water quality.

2.1.4 Factors That Affect Emissions

Emissions can vary substantially among AFOs. The substances emitted and the mass quantity of emissions depend on manure characteristics and whether the microbial breakdown of manure occurs under aerobic or anaerobic conditions. Even for a specific animal type and type of manure management system, emissions can vary from farm to farm depending on climate and a number of operational factors. The primary factors that influence emissions are outlined below. Table 2-4 explains generally how these factors affect emissions.

Factors That Increase Emissions

Substance Emitted	Wet Manure Handling	Dry Manure Handling	pH	High Temperature	Manure Residence Time	Precursors
Ammonia			>7.0	✔	✔	Nitrogen
Hydrogen sulfide	✔		<7.0	✔	✔	Sulfur
Methane	✔			✔	✔	Carbon
VOC (and HAP)	✔			✔	✔	Carbon
Particulate matter		✔				None

Differences in operating practices can affect emissions substantially. For example, dry manure management systems that are well operated will not be significant sources of hydrogen sulfide, VOC, and methane, because the manure decomposes aerobically. However, a dry system that is poorly operated due to improper design or management (e.g., excessively high animal density, inadequate ventilation, poor drainage, watering system leaks) can prevent the manure from drying and allow anaerobic microbial activity. During anaerobic decomposition, hydrogen sulfide, VOC, and methane will be emitted. As another example, manure residence time can be an important variable affecting emissions of gaseous compounds. Therefore, the frequency of manure removal (e.g., daily versus several times a day) and the length of time that manure is retained in various system components prior to land application can affect emissions.

Emissions from AFOs also can vary significantly over the year. The magnitude of variation depends primarily on the degree of seasonal variation in temperature. Because all of the gaseous compounds emitted from manure are products of microbial processes, rates of formation increase as temperature increases. In addition, with the exception of methane, these compounds are at least partially soluble in water. Solubility decreases and desorption rate increases with temperature. As an example of these effects, emissions of ammonia and other gaseous compounds from anaerobic lagoons are relatively low during winter months in cold climates but increase rapidly as lagoon temperature increases in the late spring and early summer due to increased microbial activity and volatilization. Unheated confinement facilities and storage structures for wet manure exhibit the same pattern of seasonal variation in emissions. The seasonal variation in emissions due to ambient temperature changes is greatest in cold climates. On an annual basis, however, there may be little difference in emissions from similar AFOs in cold and warm climates. Other factors that lead to emission variability are seasonal variations in the numbers of animals confined and feeding practices. Feeding practices, which affect manure characteristics (i.e., composition of volatile solids, nitrogen, and sulfur), will vary depending on animal age, stage of production (e.g., lactating versus dry dairy cows), animal performance (e.g., rate of weight gain or milk or egg production), genetics, and feeding strategies.

These and other sources of variability will lead to variations in emissions seasonally, geographically, and among similar AFOs. This variability suggests that an emission estimate based on short-term monitoring may be a poor predictor of average or typical emissions. Emission studies must be conducted over a sufficient time period to capture seasonal differences and differences in operational practices throughout animal production cycles. While some work has been conducted to study these effects, at this point, additional research is needed to develop a methodology to credibly integrate these factors into an emission estimation model.

2.2 Fate of AFO Emissions in the Atmosphere

The lifetime of AFO emissions in the atmosphere can vary from less than a day to many days depending on the substance emitted, atmospheric stability, solar radiation, precipitation, and the presence of reactive compounds in the air. Ammonia, hydrogen sulfide, and VOC can participate in atmospheric chemical reactions that influence ozone and fine particle formation, and acid deposition. Therefore, AFO emissions are converted to other compounds and deposited back to the earth in one of several forms. Emissions of greenhouse gases (methane, nitrous oxide, and carbon dioxide) are addressed by EPA's voluntary emission reduction programs and are not discussed further in this document.

2.2.1 Ammonia

Ammonia in the atmosphere can be present as both free (gaseous) ammonia and ammonium ($NH4_4^+$), which is formed when ammonia is dissolved in water. When bicarbonate (CO_3^{2-}), chloride (Cl^-), nitrate (NO_3^-), sulfite (SO_3^{2-}), or sulfate (SO_4^{2-}) ions also are present in the air, ammonium salts (e.g. ammonium nitrate and ammonium sulfate) will be formed (Novotny and Olem, 1994). These salts exist as fine particulate aerosols.

The residence time of atmospheric ammonia can vary from hours to days. Since ammonia and ammonium salts are water soluble, removal can occur by wet deposition during periods of precipitation. Otherwise, dry deposition due to gravity is the primary removal mechanism for ammonium salts and gaseous ammonia adsorbed on particulates. Gaseous ammonia also can be adsorbed directly on plant and soil surfaces. Because gaseous ammonia has a relatively short residence time in the atmosphere, it is deposited near the emission source. Depending on meteorological conditions, ammonium aerosols can be deposited close to the emission source or can be transported greater distances from the source before removal by either wet or dry deposition.

Both wet and dry ammonia deposition can cause ecological damage. Ammonia deposition can directly impair surface water quality by creating eutrophic conditions leading to fish kills and an overall decline in marine organisms. Ammonia deposition also can contribute to the acidification and consequently disruption of terrestrial and fresh water aquatic ecosystems that are acid-sensitive (van Breemen et al., 1982; ApSimon et al., 1987). Acidification occurs primarily when ammonium sulfate and ammonium sulfide are transformed to sulfuric acid by nitrification reactions that occur in soils and surface waters.

2.2.2 Hydrogen Sulfide

The residence time of hydrogen sulfide in the atmosphere can range from hours to days depending on atmospheric conditions. In the atmosphere hydrogen sulfide can be oxidized to sulfur dioxide and then sulfur trioxide, which reacts with water to form sulfuric acid. Oxidation to sulfur trioxide (sulfite) proceeds rapidly if metallic catalysts, such as iron and manganese oxides, which are common products of combustion processes, are present. If ammonia or another cation is present, a reaction to form a fine particulate aerosol will occur. If not, sulfuric acid will be formed. Because hydrogen sulfide is water soluble, removal also can occur by wet deposition. Once deposition occurs, hydrogen sulfide will be oxidized microbially to sulfuric acid. Therefore, hydrogen sulfide emissions can be responsible for the acidification of surface waters and soils both by direct deposition or following oxidation in the atmosphere to sulfate.

2.2.3 Volatile Organic Compound

The atmospheric residence time of VOC ranges from hours to months, depending on the species. Volatile organic compounds, in the presence of sunlight and nitrogen oxides, contribute to the formation of ground-level ozone, which can be transported over long distances. In addition to ozone formation, VOC species can be oxidized ultimately to carbon dioxide and water by hydroxyl radicals, oxygen, and ozone. Volatile organic compounds can be removed from the atmosphere by adhering to land and plant surfaces, and soluble VOC are removed through wet deposition.

2.2.4 Particulate Matter

Typically, the atmospheric residence time of PM ranges from one to 10 days. The length of time that particulates remain airborne varies by particle size. Larger particles settle by gravity in the vicinity of the emission source, and fine particulates are transported farther downwind (similar to gaseous compounds). Particulates are removed by both wet and dry deposition.

2.3 Methods for Quantifying AFO Emissions

No standardized methods for measuring or estimating emissions from AFOs have been developed, although emissions of gaseous substances and PM from AFOs have been measured extensively using a variety of techniques. Many of the previous studies were conducted on a research scale using experimental designs and specially fabricated equipment. No consensus exists on the best methods for sampling AFO sources, and the analytical methods developed by EPA have not been validated on the matrix of gases emitted by AFOs.

Another limitation of past studies is the absence of standard measurement units that link an emission rate to the activity that was responsible for the emission. For example, some studies report emissions from anaerobic lagoons on a unit of surface area basis and others report on a unit of animal confinement capacity basis. It is difficult, if not impossible, to compare reported values among studies and delineate the effect of variables (e.g., manure loading rate, surface area-to-volume ratio) to develop valid functional relationships. The development of such relationships is essential for the formulation of credible mathematical models for predicting expected emissions for individual AFOs.

The methods that have been used historically to estimate emissions from AFOs are direct measurement and the application of emission factors. Regression analysis and process-based, mass balance approaches are estimation methods that may be developed in the future. However, each of these approaches rely on comprehensive emissions data which currently are lacking for AFO processes.

2.3.1 Direct Measurement

Few of EPA's test methods are applicable to AFO emission sources, and a consensus on standards has not been developed by other organizations. Direct measurement of emissions typically involves measuring the concentrations and flow rate from a source of interest. This approach to quantifying emissions is well suited to conventional industrial emission sources, where vent characteristics are relatively constant. However, measuring AFO emissions is difficult because of the open nature of the emission sources and the temporal and spatial variations in emissions. Moreover, emissions from open sources at AFOs are released over large surface areas at varying rates and are affected by local atmospheric conditions (e.g., wind speed and direction, background concentrations). At this time, direct measurement of most emission sources at AFOs is impractical for purposes other than conducting research.

Mechanically Ventilated Confinement

In theory, measuring emissions from enclosed confinement structures would entail measurement of concentrations and the flow rate of the mechanical ventilation system exhaust using standard methods. However, obtaining representative samples from exhaust systems that capture the diurnal and seasonal patterns is complicated by the fact that the flow rate from these systems is not constant. Rather, mechanical ventilation systems are designed to provide optimum environmental conditions (i.e., temperature and humidity) for the confined animals and, therefore, the ventilation rate varies by housing design; animal age and population density; and climatic conditions. Repeated measurements also must be made at sufficient intervals to capture variations due to production cycles and manure management practices. One common deficiency of many past studies is that emissions were measured over limited time periods that do not capture the effects of these variables.

In addition to emissions, measurements of climatic and operational parameters must also be taken. To account for background concentrations, concurrent measurements of ventilation system intake flow rates and concentrations should be taken. To relate the emission rate observed from the source to the activity ultimately responsible for the emission, production parameters (animal age, population, weight gain) and the details of the confinement facility (type of confinement, ventilation, and manure management system) should be recorded. To account for climatic effects, measurements of indoor conditions (temperature, humidity, ventilation rate) and ambient conditions (temperature, humidity) should also be made.

Open Sources

Open sources at AFOs include partially enclosed confinement structures that are not mechanically ventilated, manure stockpiles, uncovered lagoons, feedlots, and land application sites. Sampling procedures for open sources must account for local meteorological conditions. For these emission sources, both flux chamber and micrometeorological techniques have been used to measure emissions. For anaerobic lagoons, emissions of VOC can also be estimated using computer programs.

Flux chamber techniques are used to measure the emission rate (i.e., mass of emissions per unit area) primarily from small scale sources. For example, a closed-chamber is placed on or around a source and a stream of gas is withdrawn from the chamber and measured for concentration. All flux chamber techniques are limited in scale and can influence the sampling results to some degree since the conditions (e.g., temperature, wind speed) inside the chamber will differ from ambient conditions and since substances can adhere to the chamber surfaces.

Micrometeorological techniques can be used for large scale analysis (e.g., measurement of emissions from a feedlot). Typically, monitors for meteorological parameters (e.g., wind speed, temperature, insolation, humidity) and emissions monitors are placed on towers or platforms at various heights. The source emissions are determined as the difference between measurements made downwind and upwind from the source. For measuring emissions of ammonia, hydrogen sulfide, and VOC, remote sensors, such as Fourier infrared spectroscopy (FTIR) and ultraviolet differential optical absorption spectroscopy (UV-DOAS), can be used. Particulate matter emissions can be measured using gravimetric techniques (i.e., weighing the mass accumulated on a filter) or continuous monitors, such as a tapered element oscillating microbalance. Micrometeorological techniques are most applicable if the objective is to estimate aggregate emissions from an entire operation. Although micrometeorological techniques eliminate the bias created by small-scale enclosure techniques, spatial variability due to surface topography (e.g., buildings, trees, other emission sources) complicates the use of this approach.

For anaerobic lagoons, or other impoundments containing liquid manure, an estimate of VOC emissions can be obtained at a lower cost by using computer models, such as EPA's WATER9. The WATER9 model estimates emissions of individual compounds from wastewater collection, storage, treatment, and disposal facility components. The emission estimates are based on the properties of the compound and its concentration in the waste. To use this program, liquid samples must be collected and the concentrations of target compounds determined. Concentration values and design and operating parameters (e.g., depth, surface area) of the lagoon or impoundment are entered into the program to obtain an estimate of emissions. However, the validity of the WATER9 model with respect to VOC emissions from AFOs should be evaluated.

As with enclosed source sampling, the test program for open sources must be conducted over a time period that will account for emission variations due to production cycles, manure management practices, and climate. Information on AFO production parameters must be collected along with measurements of meteorological conditions (air temperature, wind speed and direction, humidity, solar radiation) and manure temperature.

2.3.2 Emission Factors

As part of a preliminary investigation into emissions from AFOs, EPA/OAQPS developed draft emission factors for AFOs based on information gathered from literature (EPA, 2001). Emission factors were developed for swine, poultry (broiler, layer, and turkey), beef, and dairy operations (Tables 2-5 through 2-8). For each animal sector, emission factors were developed for the predominant types of confinement and manure management systems used at large commercial production facilities in the U.S. The factors are expressed in terms of annual mass of emissions per unit of confinement capacity (e.g., lb/head-yr). Although veal operations can emit ammonia, hydrogen sulfide, and VOC, data on which to base emission factors for veal operations were not found. Additionally, sufficient data were not available to develop emission factors for HAP.

While nearly 500 references containing emissions data were found, the review of the applicable literature revealed that data suitable for the derivation of emission factors for AFOs are very limited. In addition, the availability of information (e.g., confinement facility size, type of waste management system) necessary to relate emissions to a unit of production capacity frequently was lacking or vague. As a result, the emission factors developed are incomplete because emission factors could not be developed for every emission point. Where sufficient information was not available from the literature review, emission factors were developed, where appropriate, based on the microbial and chemical mechanisms responsible for emissions considering manure precursors, excretion rates, and engineering judgement. In addition, some emission factors were based on relatively few data points and thus do not necessarily represent the range of emissions variability expected from the complex mechanisms that influence emissions from AFOs.

While comprehensive emission data are lacking, the draft emission factors provide some insight into the AFO emissions. The factors can be used to provide order of magnitude estimates for developing regional emission inventories, estimate relative amounts of different substances emitted, and compare relative emissions from different types of AFOs. The factors are not appropriate for estimating emissions from individual farms or for making regulatory determinations for any particular facility.

2.3.3 Regression Analysis

In a regression analysis, a statistical analysis (standard least-squares multivariate regression equations) is used to correlate emissions to a variety of independent variables (e.g., animal type, manure management system type). The analysis would be used to identify the parameters that have the greatest effect on emissions. For example, the regression analysis could be used to determine if ammonia emissions are more closely tied to the amount of protein compounds in feed, the type of manure management system, or other factors.

While this approach could produce more accurate emission estimates than emission factors, the approach requires a comprehensive data set that includes all of the parameters that are suspected of affecting emissions (e.g., animal type, animal age, AFO configuration, climatic conditions). To use this approach, additional studies need to be conducted since the available studies have generally not focused on the total emissions from all AFO components.

2.3.4 Process-based Modeling

The EPA contracted with the National Academy of Sciences (NAS) to assess the scientific issues involved with estimating emissions from AFOs. As a part of this assessment, NAS was asked to review EPA's draft report, "Emissions from Animal Feeding Operations." An interim NAS report was submitted to EPA on June 4, 2002 (NRC, 2002) and a final report was published in 2003 (NRC, 2003). The NAS report stated that generating reasonably accurate estimates of emissions from AFOs is difficult because of the complex factors that affect emissions. The NAS concluded that the emission factors available today are not adequate for characterizing all of the variables that affect emissions. Moreover, NAS stated that pursuing an emission factor approach for estimating AFO emissions may not be fruitful because of the lack of scientific data to develop the number of emission factors required. In essence, NAS concluded that there are too many variables for an emission factor approach to work for individual farms.

As an alternative, NAS recommended pursuing a process-based approach to estimating emissions at the farm and regional level. A process-based approach would begin by considering feed intake and use mass balance principles to account for the inflows, outflows, and sinks of substances as manure passes through the farm system. The approach would use mathematical modeling and experimental data to simulate conversion and transfer of reactants and products at each step, and therefore would account for the interactions between various AFO components. For example, a process-based model would account for the fact that ammonia emitted from an anaerobic lagoon would not be available for emission from a land application site. The use of a mass balance approach would prevent the prediction of higher gaseous emissions than are possible given the chemical precursors in the manure.

The process-based approach would be used for gaseous emissions that are generated from manure precursors (e.g., ammonia, nitrous oxide, hydrogen sulfide). The approach could not be applied to PM since these emissions are from entrainment of dried materials rather than formed from manure breakdown.

At this time, available data are not sufficient to develop process-based models with a high degree of accuracy. One area of research in which data are lacking is the conversion mechanisms that govern formation of gaseous substances from manure precursors. Also, the composition of feeds and manure can vary substantially from farm to farm based on individual animal management practices. Data on average or typical values may not be representative of any given farm. Therefore, substantial new data collection and research will be needed to develop the process-based models.

2.4 Mitigation Techniques

Potential control technologies for reducing emissions from AFO processes were identified from a literature search that included journals, conference proceedings, and research reports that were published during a 13-year period (up to Jan 2004). While a number of technologies were identified, relatively little research has been conducted to quantify the costs and long-term effectiveness of these technologies. Many of the control technology studies have focused on mitigating odors at particular locations or reducing emissions from a single source (e.g., a confinement house for purposes of protecting animal or worker health). These studies often do not address the fact that emissions reduced at one AFO component (e.g., confinement) may be emitted later at another component (e.g., manure storage) or that methods to control one pollutant may increase emissions of others. Control technology effectiveness, therefore, must be evaluated based on the design characteristics of each AFO and the effect on total emissions from the entire operation (i.e., confinement, manure management systems, and land application) for each substance of concern.

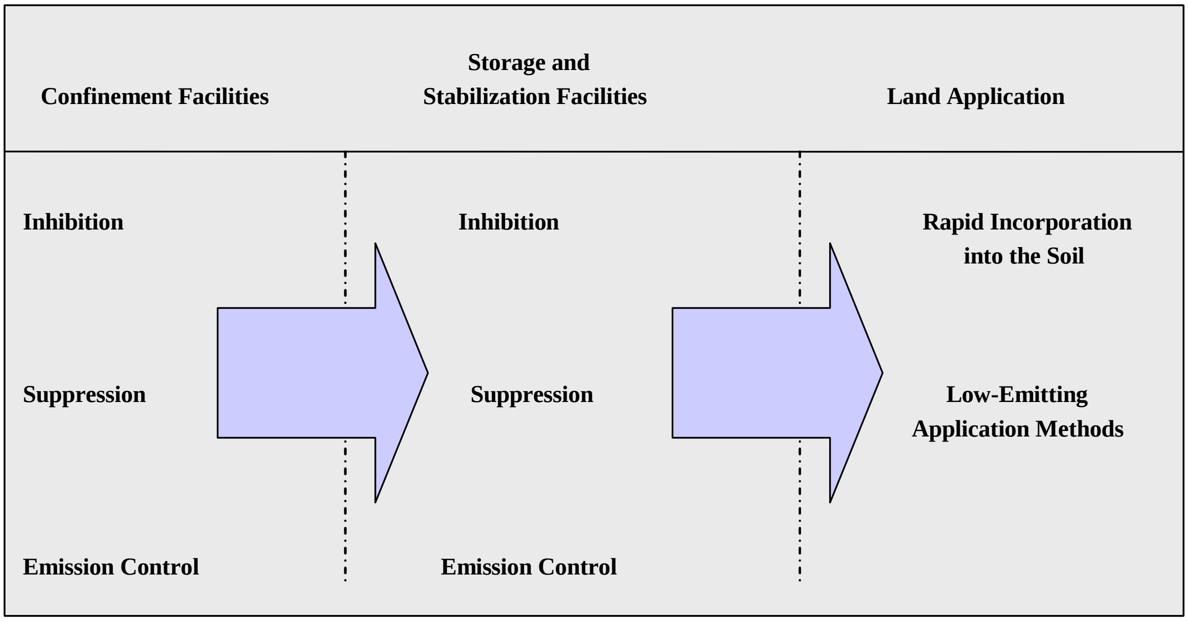
There are three strategies for reducing emissions from AFO processes:

- Inhibiting the formation of substances,
- Suppressing emissions of substances once formed, and
- Capturing and controlling substances emitted.

Emission control strategies for AFOs can involve different combinations of inhibition, suppression, and control techniques (Figure 2-1). For example, one facility may choose to inhibit and suppress emissions from various emission points and control at a single downstream location. Another facility may choose to control at the points of emission generation (i.e., confinement, storage, land application). The availability of control strategies is highly site specific, depending on the objectives of control, the types of manure management systems that are currently in place, and climate. In some instances, different control strategies may be required for different pollutants.

Inhibition Techniques

Inhibition techniques are essentially pollution prevention methods that either reduce the amount of nitrogen and sulfur in manure (e.g., diet modification) or that remove the conditions that favor formation of ammonia and hydrogen sulfide once excreted. There are three strategies for inhibiting formation of gaseous substances (primarily hydrogen sulfide and ammonia): (1) reduction of the excreted precursor compounds through diet modification; (2) manure additives to inhibit microbial processes, and (3) design practices to reduce anaerobic conditions. Although inhibition techniques are not expected to result in emission reductions that are comparable to add-on control technologies, inhibition techniques reduce unnecessary emissions.



Note: Different combinations may be used for different manure streams within a single AFO. (e.g., solid and liquid wastes at a dairy)

Figure 2-1. AFOs Can Use a Variety of Different Techniques to Control Emissions

Suppression Techniques

Suppression techniques prevent the release of PM or gases (ammonia and hydrogen sulfide and VOC, that are highly soluble in water) once they have been generated (e.g., covering of manure storage tanks). Because suppression does not physically alter or destroy substances, they can be emitted when manure is transferred to a downstream location that is not controlled. For example, covering a manure storage pond or lagoon will contain ammonia but does not prevent subsequent release at the land application site unless the manure is rapidly incorporated into soil.

Control Techniques

Control techniques can reduce emissions of PM and gases by either capturing emissions or by physically altering the chemical composition of the compounds (e.g., biological covers on anaerobic lagoons will convert hydrogen sulfide to sulfur dioxide).

Table 2-9 summarizes the some of various inhibition, suppression, and control techniques that have been identified. The techniques are grouped according to their application: confinement; manure handling and storage; or land application site. While there are many technologies that have been evaluated on a farm-scale basis or are being utilized to some degree in animal agriculture or similar industrial processes, many techniques identified in Table 2-9 have been demonstrated only in a limited variety of commercial operating conditions. The performance of these technologies will vary depending on animal type, local design and operating scenarios, and climate.

2.5 References

Andersson, 1998. "Reducing Ammonia Emissions by Cooling of Manure in Manure Culverts." In: Nutrient Cycling in Agroecosystems. Vol. 51, 1998. pp. 73-79.

Alexander, 1977. Introduction of Soil Microbiology. John Wiley and Sons, New York, New York.

Alexander, 1999. Biodegradation and Bioremediation, 2nd Edition. Academic Press, San Diego, California.

Aneja, V.P., J.P. Chauhan, and J.T. Walker. 2000 "Characterization of Atmospheric Ammonia Emissions from Swine Waste Storage and Treatment Lagoons." Journal of Geophysical Research, Vol. 105. pp. 11535-11545.

ApSimon, H.M., M. Kruse, and J.N.B. Bell. 1987. Ammonia Emissions and Their Role in Acid Deposition. Atmospheric Environment. 21:1939-1946.

Asman, 1992. "Ammonia Emission in Europe: Updated Emission and Emission Variation." RIVM Report No. 228471008. National Institute of Public Health and Environmental Protection, Bilthoven, Netherlands.

Battye, R., W. Battye, C. Overcash, and S. Fudge. 1994. Development and Selection of Ammonia Emission Factors: Final Report. U.S. EPA. EPA Publication No. EPA-600/R-94-190.

Demmers, Phillips, Short, Burgess, Hoxey, and Wathes. 2001. "Validation of Ventilation Rate Measurement Methods and the Ammonia Emission from Naturally Ventilated Dairy and Beef Buildings in the United Kingdom." Journal of Agricultural Engineering Research. Vol. 79, No. 1. pp. 107-116.

Fulhage, C.D. 1998. "Gaseous Emissions from Manure Management Systems." American Society of Agricultural Engineers. ASAE Meeting Presentation Paper No. 98-4055.

Grady, C.P.L., Jr. and H.C. Lim. 1980. Biological Wastewater Treatment: Theory and Applications. Marcal Dekker, Inc., New York, New York.

Grelinger, M. 1997. "Improved Emission Factors for Cattle Feedlots." In: Emissions Inventory: Planning for the Future, An EPA/A&WMA Specialty Conference. October 28-30. pp. 515-523.

Grelinger and Page. 1999. Air Pollution Emission Factors for Swine Facilities. Air and Waste Management Association Conference Proceedings. October 26-28.

Groot Koerkamp, P.W.G., J. Metz, G.Uenk, V.R. Phillips, M.R. Holden, and R.W. Sneath. 1998. "Concentrations and Emissions of Ammonia in Livestock Buildings in Northern Europe." Journal of Agricultural Engineering Research. Vol. 70. pp. 79-95.

Harris, D.B. and E.L. Thompson, Jr. 1998. "Evaluation of Ammonia Emissions from Swine Operations in North Carolina." In: Emission Inventory --Living in a Global Environment. VIP-88. Air & Waste Management Association, Pittsburgh, PA. pp. 420-429.

Hartung, J.V. and R. Phillips. 1994. "Control of Gaseous Emissions from Livestock Buildings and Manure Stores." Journal of Agricultural Engineering Research. Vol. 57, May. pp. 173-189.

Heber, A., R. Duggirala, and J. Ni. 1997. "Manure Treatment to Reduce Gas Emissions from Large Swine Houses." In: Proceedings from the International Symposium on Ammonia and Odour Control from Animal Production Facilities. Netherlands. pp. 449-457.

Hoeksma, P., N. Verdoes, and G.J. Monteny. 1993. "Two Options for Manure Treatment to Reduce Ammonia Emission from Pig Housing." In: Proceedings of the First International Symposium on Nitrogen Flow in Pig Production and Environmental Consequences, EAAP Publication No. 69. Wageningen. pp. 301-306.

Hutchinson, G.L., A.R. Mosier, and C.E. Andre. 1982. "Ammonia and Amine Emissions from a Large Cattle Feedlot." Journal of Environmental Quality, Vol.11, No. 2. pp. 288-293.

Jacobson, L.D., D. Paszek, R. Nicolai, D. R. Schmidt, B. Hetchler, and J. Zhu. 1999. "Odor and Gas Emissions from Animal Manure Storage Units and Buildings." American Society of Agricultural Engineers Annual International Meeting. July 18-22.

Jungbluth, T. and E. Hartung. 1997. "Determination of the Odor Plume Boundaries from Animal Houses." In: Livestock Environment V: 5th International Symposium. American Society of Agricultural Engineers. May 29-31. Bloomington, MN.

Koelliker, J.K., J.R. Miner. 1973. "Desorption of Ammonia from Anaerobic Lagoons." In: ASAE Transactions. pp. 148-151.

Kroodsma, W, Scholtens, and Huis. 1988. "Ammonia Emission from Poultry Housing Systems." In: Odour and Ammonia Emissions from Livestock Farming. pp. 152-161.

Loehr, 1984. Pollution Control for Agriculture, 2nd Edition. Academic Press, Orlando, Florida.

Martin, J. 2000. "A Comparison of the Performance of Three Swine Waste Stabilization Systems." Paper submitted to Eastern Research Group, Inc. in October.

Misselbrook, T.H., B.F. Pain, and D.M. Headon. 1998. “Estimates of Ammonia Emission from Dairy Cow Collecting Yards.” Journal of Agricultural Engineering Research. Vol 71. pp. 127-135.

National Research Council (NRC). 2002. “The Scientific Basis for Estimating Air Emissions from Animal Feeding Operations.” Washington, D.C.: National Academy Press.

National Research Council (NRC). 2003. “Air Emissions from Animal Feeding Operations: Current Knowledge, Future Needs.” Washington, D.C.: National Academy Press.

Ni, J., A. Heber, C. Diehl, and T. Lim. 2000a. “Ammonia, Hydrogen Sulphide and Carbon Dioxide Release from Pig Manure in Under Floor Deep Pits.” Journal of Agricultural Engineering Research. Vol. 77, No. 1. September. pp. 53-66.

Ni, J., A. Heber, T. Lim, R. Duggirala, B. Haymore, C. Diehl, and A. Sutton. 2000b. “Continuous Measurement of Hydrogen Sulfide Emission from Two Large Swine Finishing Buildings.” ASAE Paper No. 99-4132. American Society of Agricultural Engineers. p. 14.

Ni, J., A. Heber, T. Lim, and C. Diehl. 2000c. “Ammonia Emission from a Large Mechanically-Ventilated Swine Building During Warm Weather.” Journal of Environmental Quality. 29:751-758.

Novotny, V. and H. Olem. 1994. “Water Quality: Prevention, Identification, and Management of Diffuse Pollution.” Van Nostrand Reinhold, New York, New York.

O’Neil, D.H., U.R. Phillips, 1992. “A Review of the Control of Odor Nuisance from Livestock Buildings: Part 3, Properties of the Odorous Substances Which Have Been Identified in Livestock Wastes or in the Air about Them.” Journal of Agricultural Engineering Research.

Oosthoek, J., W. Kroodsma, and P. Hoeksma. 1991. “Ammonia Emissions from Dairy and Pig Housing Systems.” In: Odour and Ammonia Emissions from Livestock Farming. eds. V.C. Nielsen, J.H. Voorburg, and P. L'Hermite. p. 31.

Secrest, C. 1999. “Field Measurement of Air Pollutants Near Swine Confined Animal Feeding Operations Using UV DOAS and FTIR.” U.S. Environment Protection Agency, Office of Research and Development, Air Enforcement Division. Washington, DC.

Sweeten, J.M., L. Erickson, P. Woodford, C.B. Parnell, K. Thu, T. Coleman, R. Flocchini, C. Redder, J.R. Master, W. Hambleton, G. Bluhm, and D. Tristao. 2000. “Air Quality Research & Technology Transfer Programs for Concentrated Animal Feeding Operations.” Presented to USDA Agricultural Air Quality Task Force. July 18-20.

Takai, H., S. Pedersen, J.O. Johnsen, J.H.M. Metz, P.W.G. Groot Koerkamp, G.H., Uenk, V.R Phillips, M.R. Holden,,R.W. Sneath, J.L. Short, R.P. White, J. Hartung, J. Seedorf, M. Schröder, K.H. Linkert, and C.M. Wathes. 1998. "Concentrations and Emissions of Airborne Dust in Livestock Buildings in Northern Europe." Journal of Agricultural Engineering Research. 70:59-77.

Tamminga, S. 1992. "Gaseous Pollutants by Farm Animal Enterprises." In: Animals and the Environment. Ch. 20, pp. 345-357. CAB International.

Valli, L., S. Piccinini, and G. Bonazzi. 1991. "Ammonia Emissions from Two Poultry Manure Drying Systems." In: Odour and Ammonia Emissions from Livestock Farming. pp. 50-58.

van Breemen, N., P.A. Burrough, E.J. Velthorst, H.F. van Dobben, T. de Witt, T. B. Ridder, and H.F.R. Reijnders. 1982. "Soil Acidification from Atmospheric Ammonium Sulfate in Forest Canopy Throughfall." Nature 299: 548-550.

Van der Hoek, K.W. 1998. "Estimating Ammonia Emission Factors in Europe: Summary of the Work of the UNECE Ammonia Expert Panel." Atmospheric Environment. Vol 32, No. 3. pp. 315-316.

Witter, E. 1991. "Use of $CaCl_2$ to Decrease Ammonia Volatilization after Application of Fresh and Anaerobic Chicken Slurry to Soil." Journal of Soil Science. 42: 369-380.

Yang, P., J.C. Lorimore, and H. Kim. 2000. "Nitrogen Losses from Laying Hen Manure in Commercial High-Rise Layer Facilities." Transactions of the ASAE. Vol. 43, No. 6. pp. 1771-1780.

U.S. Environmental Protection Agency (EPA). 2001. "Emissions from Animal Feeding Operations (Draft)." EPA Contract 68-D-6-0011. Washington, D.C.

Zhu, J., L. Jacobson, D. Schmidt, and R. Nicolai. 2000. "Daily Variations in Odor and Gas Emissions From Animal Facilities." Applied Engineering in Agriculture. Vol. 16(2): 153-158.

Table 2-1. Substances Potentially Emitted from Animal Feeding Operations

Animal Sector	Operations	Ammonia	VOC[a]	Hydrogen Sulfide	Methane	Particulate Matter	Nitrous Oxide
Boilers, Turkeys, Layers (dry)	Confinement	✔				✔	
	Manure Storage and Treatment	✔				✔	
	Land Application	✔				✔	✔
Layers (liquid)	Confinement	✔	✔	✔	✔	✔	
	Manure Storage and Treatment	✔	✔	✔	✔		
	Land Application	✔	✔	✔			✔
Swine (flush, pit storage, pull plug pits, and pit recharge systems)	Confinement	✔	✔	✔		✔	
	Manure Storage and Treatment	✔	✔	✔	✔		
	Land Application	✔	✔	✔			✔
Dairy (flush and scrape systems)	Confinement	✔	✔	✔		✔	
	Manure Storage and Treatment	✔	✔	✔	✔		
	Land Application	✔	✔	✔			
Veal	Confinement	✔	✔	✔		✔	
	Manure Storage and Treatment	✔	✔	✔	✔		
	Land Disposal	✔	✔	✔		✔	✔
Beef and dairy (drylot)	Confinement	✔	✔	✔	✔	✔	✔
	Manure Storage and Treatment	✔	✔	✔	✔	✔	✔
	Land Disposal	✔	✔	✔		✔	✔

[a] A small portion of volatile organic compounds emitted from AFOs are hazardous air pollutants.

Table 2-2. Types of Confinement Systems

Confinement System	Description	Animal Sector
Deep-pit house	A structure in which animal confinement and long-term manure storage are integrated into a single building typically constructed of concrete. Animals are confined in the upper level and manure falls through totally or partially slatted flooring. Deep-pit structures can be totally or partially enclosed.[a]	Swine
Feedlot (drylot)	An open lot without vegetation where animal nutritional requirements are satisfied by feedstuffs (e.g., hay, silage, grains). The feedlot surface may be paved but such practice is generally limited to a concrete apron typically located along feed bunks and around water supplies since these areas have the heaviest animal traffic and manure accumulation.	Beef cattle, dairy cattle
Flush house	A structure in which animals are confined on totally or partially slatted flooring and manure is periodically flushed from the confinement structure to manure handling and storage processes (e.g., anaerobic lagoon) using liquid (e.g., water, supernatant from an anaerobic lagoon). Flush houses can be totally or partially enclosed.[a]	Swine, dairy, poultry (layers)
Freestall barn	A totally or partially enclosed structure where animals are grouped in large pens with free access to feed, water, and resting stalls.[a] Animals may or may not have access to outside areas (e.g., pasture for exercise and grazing). Typically, the areas outside the stalls where the heaviest manure accumulation occurs (e.g., the alleys between the stalls and feed bunks) are paved to facilitate removal of manure.	Dairy cattle
High-rise house	A totally or partially enclosed structure with rows of cages that are suspended above a porous surface (e.g., gravel, soil).[a] Manure passes through the suspended cages is accumulated beneath the cages and is periodically removed. High-rise structures can be totally or partially enclosed.[a]	Poultry (layers)

Table 2-2. Types of Confinement Systems (Continued)

Confinement System	Description	Animal Sector
Hoop structure	Low cost, semi-cylindrical housing in which pigs are raised on a floor of packed bedding and manure that accumulates as the pigs grow. Concept is similar to a poultry house with litter. Hoop structures are typically naturally ventilated.	Swine
House with litter	Animals are housed on a soil floor covered with dry litter (e.g., sawdust, peanut hulls) that absorbs excreted manure and moisture. Houses can be totally or partially enclosed.[a]	Poultry (broilers, turkeys)
Pasture	An open lot where animal nutritional requirements are satisfied primarily by grazing from the confinement surface. A pasture-based operation is not considered to be an AFO. However, at some AFOs, animals (e.g., dairy heifers, dry milk cows) may be confined on pasture for portions of the production cycle.	Beef cattle, dairy cattle, swine
• Pit recharge house 1.01 Pull-plug pit house	A structure in which animals are confined on slatted flooring and manure is temporarily accumulated beneath the confinement flooring. Confinement houses can be totally or partially enclosed.[a]	Swine
Scraped	A totally or partially enclosed structure in which manure (and bedding, if used) is removed from the confinement area using scrapers (e.g., tractor-mounted scrapers, chain-pulled scrapers). Where a mechanical scraper system is used to remove manure, the confinement flooring typically is sloped so that manure flows to a gutter or alley to facilitate removal.	Swine, dairy, poultry (layers)

[a] Totally enclosed structures (i.e., a roof with four permanent walls) are equipped with mechanical ventilation systems to maintain suitable humidity and temperature conditions for animals inside the confinement area and to minimize animal exposure to toxic gases (e.g., NH_3, H_2S). Partially enclosed structures can be equipped with movable curtain sidewalls and rely primarily on the natural ventilation to control climatic conditions inside the confinement area, although ventilation can be supplemented with mechanical systems.

Table 2-3. Manure Management Systems

Confinement System	Manure Management System
Deep-pit	Manure (liquid or slurry) accumulated in the pit is pumped from the pit once or twice a year. The manure may be directly applied to land or transferred to storage tanks or earthen storage ponds for later land application.
Flush	Manure is flushed from the confinement area to manure handling and storage processes daily or more frequently. Typically, an anaerobic lagoon is used to provide storage and to stabilize the manure prior to land application. Manure, particularly dairy manure, may be flushed to a solids separation process prior to storage.
Feedlot (drylot)	Accumulated manure (in solid form) is periodically scraped from the feedlot surface into stockpiles for storage prior to land application. Runoff from rainfall drains to a storage pond or anaerobic lagoon.
High-rise	Accumulated manure (in solid form) is removed annually from beneath the cages and sent to land application.
• Hoop structure • House w/litter (or bedding)	Accumulated manure and litter (in solid form) are periodically removed to storage (e.g., uncovered stockpiles) and confinement replaced with fresh litter after cleaning of the confinement area. Manure and litter may be stored in open or covered stockpiles before ultimately being disposed of by land application.
Pit recharge	Manure accumulated in the pit beneath the confinement flooring is drained periodically (e.g., every four to seven days) by gravity to manure handling and storage processes. After the manure is drained, the pit is partially refilled with liquid (e.g., supernatant from the anaerobic lagoon). Typically, an anaerobic lagoon is used to provide storage and to stabilize the manure prior to land application.

Table 2-3. Manure Management Systems (Continued)

Confinement System	Manure Management System
Pull-plug pit	Operation is similar to pit-recharge system except that the pit is drained less frequently (e.g., every one to two weeks) and liquid is not added back to the drained pit. Typically, an anaerobic lagoon is used to provide storage and to stabilize the manure prior to land application.
Scraped	The frequency of manure removal depends on operator requirements and seasonal considerations (e.g., a mechanical scrape system may be operated continuously during cold weather to prevent the blade from freezing to the floor). Manure may be stored (e.g., uncovered stockpiles) or directly applied to land.

Table 2-4. How Factors Increase Emissions

Parameter	Effect on Emissions
pH	The manure pH affects the partitioning between ammonia and hydrogen sulfide and their ionized, nonvolatile forms. Under acidic conditions (pH less than 7.0), ammonium is the predominate species and ammonia volatilization occurs at a lower rate than at higher pH values. Conversely, the potential for hydrogen sulfide emissions increases as the pH shifts from alkaline to acidic. The pH of manures handled as solids can be in the range of 7.5 to 8.5, which results in fairly rapid ammonia volatilization. Manure handled as liquids or semi-solids tends to have lower pH (ranging from 5.5 to 6.5).
Temperature	Temperature affects gas phase vapor pressure, and therefore, the volatility. For substances that are soluble in water (ammonia, some VOC, hydrogen sulfide, and other reduced sulfur compounds), emissions will be greater at higher temperatures. Emission rates of these substances will be greater in warmer climates and in the summer rather than winter. Higher temperature favors the microbial processes that generate methane and other substances.
Time in storage	Long periods of manure residence time in either confinement, storage, or stabilization facilities provide greater opportunities for anaerobic breakdown and volatilization to the air. Also, masses of substances emitted will increase with time.
Precursors	The amount of sulfur ingested by an animal will affect the potential for hydrogen sulfide production in manure. Sulfur can be present in feed additives and, in some cases, from water supplies. The amount of nitrogen in feed (proteins and amino acids) affects ammonia emission potential.
Presences of anaerobic vs. aerobic conditions	Anaerobic conditions, such as when manure is handled as a liquid or slurry, increase the potential for generation of hydrogen sulfide (and other reduced sulfur compounds), methane, and VOC. Ammonia will be generated under both aerobic and anaerobic conditions (i.e., dry and wet manure).
Moisture content	Manures with high moisture content (e.g., liquid and slurry manure) are not sources of PM emissions. The potential for PM emissions from solid manure management systems, open feedlots, and confinement houses that use bedding increases as the manure moisture content decreases.

Table 2-5. Swine Emission Factors

Emission Source	Substance Emitted	References	Number of Emission Factors	Mean Emission Factor (lb/yr-head capacity)	Statistical Relevancy Ranking[a]
Swine houses w/lagoon systems[b]	H_2S	1.02 Jacobson, et al. (1999)	1	0.0002	Very low
	NH_3	1.03 Andersson (1998) 1.04 Harris and Thompson (1998) 1.05 Heber, et al. (1997) 1.06 Oosthoek, et al. (1991)	5	6.0	High
	PM	1.07 Grelinger and Page (1999) 1.08 Takai, et al. (1998)	6	2.2	Medium
	VOC	None available	0	Not available	Not applicable
House w/pit storage	H_2S	1.09 Jacobson, et al. (1999) 1.10 Ni, et al. (2000a) 1.11 Ni, et al. (2000b) 1.12 Zhu, et al. (2000)	9	0.37	Medium
	NH_3	1.13 Asman (1992) 1.14 Hoeksma, et al. (1993) 1.15 Ni, et al. (2000c) 1.16 Oosthoek, et al. (1991) 1.17 Secrest (1999) 1.18 Sweeten, et al. (2000)	9	7.3	High
	PM	1.19 Takai, et al. (1998) 1.20 Grelinger and Page (1999)	6	2.2	Medium
	VOC	None available	0	Not available	Not applicable
Outdoor confinement	H_2S NH_3 PM VOC	None available	0	Not available	Not applicable
Anaerobic lagoon	H_2S	1.21 Jacobson, et al. (1999) 1.22 Grelinger and Page (1999)	3	1.24	Low

Emission Source	Substance Emitted	References	Number of Emission Factors	Mean Emission Factor (lb/yr-head capacity)	Statistical Relevancy Ranking[a]
	NH_3	1.23 Aneja, et. al. (2000) 1.24 Fulhage (1998) 1.25 Koelliker and Miner (1971) 1.26 Martin (2000)	6	13.9	High
	PM	None available	0	Not expected	Not applicable
	VOC	Note c	0	0.96	Not applicable
External Storage (open tanks, ponds)	H_2S	None available	0	Not available	Not applicable
	NH_3				
	PM	None available	0	Not expected	Not applicable
	VOC		0	Not available	

Emission Source	Substance Emitted	References	Number of Emission Factors	Mean Emission Factor (lb/yr-head capacity)	Statistical Relevancy Ranking[a]
	PM	None available	0	Not expected	Not applicable
	VOC	Note c	0	0.96	Not applicable
External Storage (open tanks, ponds)	H_2S	None available	0	Not available	Not applicable
	NH_3				

[a]The statistical relevancy ranking is based on the ratio of the 95 percent confidence interval and the mean of the available emission factors.
[b]Swine houses with lagoon systems include flush houses, houses with pit recharge, and houses with pull plug pits.
[c]This emission factor was calculated using a volatile solids-to-VOC conversion factor (i.e., one percent of the methane production potential).

Table 2-6. Poultry Emission Factors

Emission Source	Substance Emitted	References	Number of Emission Factors	Mean Emission Factor (lb/yr-bird capacity)	Statistical Relevancy Ranking[a]
Broiler house with bedding	H_2S	1.27 Jacobson, et al. (1999)	1	0.0018	Very low
	NH_3	1.28 Asman (1992) 1.29 Groot Koerkamp, et al. (1998) 1.30 Kroodsma, et al. (1988) 1.31 Tamminga (1992) 1.32 Van der Hoek (1998)	8	0.22	High
	PM	1.33 Takai, et al. (1998)	4	0.13	Medium
	VOC	None available	0	Negligible[b]	Not applicable
Covered storage of broiler cake	H_2S	None available	0	Negligible[b]	Not applicable
	NH_3	1.34 Van der Hoek (1998)	1	0.044	Very low
	PM	None available	0	Not available	Not applicable
	VOC		0	Negligible[b]	
Open storage of broiler litter	H_2S	None available	0	Not available	Not applicable
	NH_3	1.35 Van der Hoek (1998)	1	0.044	Very low
	PM	None available	0	Not available	Not applicable
	VOC		0	Negligible[b]	
Land application broiler solid manure	H_2S	None available	0	Negligible[b]	Not applicable
	NH_3	1.36 Van der Hoek (1998) 1.37 Battye, et al. (1994)	2	0.234	High
	PM	None available	0	Not available	Not applicable
	VOC		0	Negligible[b]	
Caged layer house with wet systems	H_2S	None available	0	Not available	Not applicable
	NH_3	1.38 Hartung and Phillips (1994) 1.39 Kroodsma, et al. (1988)	3	0.25	Medium
	PM	None available	0	Not available	Not applicable
	VOC				

Table 2-6. Poultry Emission Factors (Continued)

Emission Source	Substance Emitted	References	Number of Emission Factors	Mean Emission Factor (lb/yr-bird capacity)	Statistical Relevancy Ranking[a]
Caged layer house with dry systems	H_2S	None available	0	Not available	Not applicable
	NH_3	1.40 Valli, et al. (1991) 1.41 Yang, et al. (2000)	2	0.89	High
	PM	None available	0	Not available	Not applicable
	VOC				

Table 2-6. Poultry Emission Factors (Continued)

Emission Source	Substance Emitted	References	Number of Emission Factors	Mean Emission Factor (lb/yr-bird capacity)	Statistical Relevancy Ranking[a]
Anaerobic lagoon (layer)	H_2S	Note c	0	0.06	Not applicable
	NH_3	Note c	0	0.67	Not applicable
	PM	None available	0	Not expected	Not applicable
	VOC	Note d	0	0.04	Not applicable
Layer solid and liquid manure land application	H_2S		0	Not available	Not applicable
	NH_3	1.42 Battye, et al. (1994) 1.43 Van der Hoek (1998) 1.44 Witter (1991)	3	0.33	Medium
	PM	None available	0	Not available	Not applicable
	VOC				
Turkey house with bedding	H_2S	1.45 Jacobson, et al. (1999)	1	0.007	Very low
	NH_3	1.46 Asman (1992) 1.47 Van der Hoek (1998)	2	1.12	Medium
	PM	None available	0	Not available	Not applicable
	VOC		0	Not expected	
Covered turkey litter storage	H_2S	None available	0	Negligible[b]	Not applicable
	NH_3	1.48 Van der Hoek (1998)	1	0.13	Very low
	PM	None available	0	Not available	Not applicable
	VOC		0	Not expected	
Open turkey litter storage	H_2S	None available	0	Negligible[b]	Not applicable
	NH_3	1.49 Van der Hoek (1998)	1	0.13	Very low
	PM	None available	0	Not available	Not applicable
	VOC		0	Negligible[b]	

Table 2-6. Poultry Emission Factors (Continued)

Emission Source	Substance Emitted	References	Number of Emission Factors	Mean Emission Factor (lb/yr-bird capacity)	Statistical Relevancy Ranking[a]
Turkey solid manure land application	H_2S	None available	0	Negligible[b]	Not applicable
	NH_3	1.50 Battye, et al. (1994) 1.51 Van der Hoek (1998)	2	1.008	Very low
	PM	None available	0	Not available	Not applicable
	VOC		0	Negligible[b]	

[a]The statistical relevancy ranking is based on the ratio of the 95 percent confidence interval and the mean of the available emission factors.
[b]Assumes aerobic conditions are maintained.
[c]This emission factor was calculated using the emission factor for swine anaerobic lagoons. Although manure characteristics vary between animal types, the formation and volatilization mechanisms in anaerobic lagoons should not be different. Therefore, the swine emission factor was adjusted to reflect the different manure loading to the lagoon, based on the manure excretion rate for poultry.
[d]This emission factor was calculated using a volatile solids-to-VOC conversion factor (i.e., one percent of the methane production potential).

Table 2-7. Beef Emission Factors

Emission Source	Substance Emitted	References	Number of Emission Factors	Mean Emission Factor (lb/yr-head capacity)	Statistical Relevancy Ranking[a]
Drylot	H_2S	None available	0	Negligible[b]	Not applicable
	NH_3	1.52 Grelinger (1997) 1.53 Hutchinson, et al. (1982) 1.54 Sweeten, et al. (2000)	3	25.2	Low
	PM 10	1.55 Grelinger (1997) 1.56 Sweeten, et al. (2000)	2	12.6	Very low
	VOC	None available	0	Negligible[b]	Not applicable
Storage pond	H_2S	None available	0	Not available	Not applicable
	NH_3				
	PM		0	Not expected	
	VOC		0	Not available	
Stockpile	H_2S	None available	0	Negligible[b]	Not applicable
	NH_3		0	Not available	
	PM				
	VOC		0	Negligible[b]	
Solid manure land application	H_2S	None available	0	Negligible[b]	Not applicable
	NH_3	1.57 Battye, et al. (1994) 1.58 Van der Hoek (1998)	2	17.0	Very low
	PM	None available	0	Not available	Not applicable
	VOC		0	Negligible[b]	

[a]The statistical relevancy ranking is based on the ratio of the 95 percent confidence interval and the mean of the available emission factors.
[b]Assumes aerobic conditions are maintained.

Table 2-8. Dairy Emission Factors

Emission Source	Substance Emitted	References	Number of Emission Factors	Mean Emission Factor (lb/yr-head capacity)	Statistical Relevancy Ranking[a]
Free-stall barn (scrape)	H_2S	None available	0	Not available	Not applicable
	NH_3	1.59 Demmers, et al. (2001) 1.60 Jungbluth and Hartung (1997) 1.61 Misselbrook, et al. (1998) 1.62 Van der Hoek (1998)	4	18.5	Medium
	PM	None available	0	Not available	Not applicable
	VOC				
Drylot	H_2S	None available	0	Negligible[b]	Not applicable
	NH_3	1.63 Misselbrook, et al. (1998) 1.64 Sweeten, et al. (2000)		18.6	Very low
	PM 10	1.65 Takai, et al. (1998)	1	3.2	Very low
	VOC	None available	0	Negligible[b]	Not applicable
Flush barn and storage pond	H_2S	None available	0	Not available	Not applicable
	NH_3				
	PM				
	VOC				
Milking parlor	H_2S	None available	0	Note c	Not applicable
	NH_3				
	PM				
	VOC				
Anaerobic lagoon	H_2S	Note d	0	7.14	Not applicable
	NH_3	Note d	0	118.14	Not applicable
	PM	None available	0	Not expected	Not applicable
	VOC	Note e	0	6.43	Not applicable
Liquid manure land application	H_2S	None available	0	Not available	Not applicable
	NH_3	1.66 Van der Hoek (1998)	1	44.6	Very low
	PM	None available	0	Not available	Not applicable
	VOC				

Table 2-8. Dairy Emission Factors (Continued)

Emission Source	Substance Emitted	References	Number of Emission Factors	Mean Emission Factor (lb/yr-head capacity)	Statistical Relevancy Ranking[a]
Solids storage	H_2S	None available	0	Negligible[b]	Not applicable
	NH_3		1	13.9	Very low
	PM		0	Not available	Not applicable
	VOC		0	Negligible[b]	

[a]The statistical relevancy ranking is based on the ratio of the 95 percent confidence interval and the mean of the available emission factors.
[b]Assumes aerobic conditions are maintained.
[c]Emissions from milking parlors are not expected due to frequent flushing of manure from the area with fresh water.
[d]This emission factor was calculated using the emission factor for swine anaerobic lagoons. Although manure characteristics vary between animal types, the formation and volatilization mechanisms in anaerobic lagoons should not be different. Therefore, the swine emission factor was adjusted to reflect the different manure loading to the lagoon, based on the manure excretion rate for dairy cattle.
[e]This emission factor was calculated using a volatile solids-to-VOC conversion factor (i.e., one percent of the methane production potential).

Table 2-9. Potential Control Technologies for Reducing Emissions from AFO Processes

Control Technology	Animal Sector	Applicable AFO Processes	Pollutants Controlled	Control Effectiveness [a] (%)	Comments
Inhibition Techniques					
Confinement Facilities					
Diet modification - nutrient optimization - digestive optimization	All	Indoor confinement Manure management system Land application	NH_3, H_2S	10 - 17% (NH_3)[b] Not available (H_2S)	The reduction of NH_3 emissions achieved by optimizing the protein level in feeds may be marginal because farmers do not substantially over-feed proteins beyond the nutritional requirements, due to cost concerns (protein feedstuffs are expensive). Greater NH_3 emission reductions could be achieved from improving the animal's digestion of proteins resulting in reduction of non-adsorbed protein. Although not currently practiced, H_2S emissions could be reduced by reducing sulfur intake to the level of nutritional requirements.
Conversion from wet to dry manure management	Poultry (layers), swine	Indoor confinement	NH_3, H_2S CH_4, VOC	Not available	The potential for formation of NH_3, H_2S, CH_4 and VOC is reduced when manure is handled as a solid. However, dry manure is a source of PM emissions.
Solid separation	Swine	Indoor confinement	NH_3, H_2S	Not available	To reduce anaerobic conditions, urine can be drained from manure via sloped floor with channels running parallel to slope; manure solids are collected (e.g., using scraper).
Belt system for solid manure collection	Poultry (layers), swine	Indoor confinement	NH_3	Not available	Manure collected on conveyor belt below cages or a slotted floor; solids remain on belt, liquids drain from belt into trough. With belt systems, manure may be removed as frequently as daily and applied directly to cropland or stored for application later. However, removal may be less frequent if partial drying is desired.

Table 2-9. Potential Control Technologies for Reducing Emissions from AFO Processes (Continued)

Control Technology	Animal Sector	Applicable AFO Processes	Pollutants Controlled	Control Effectiveness [a] (%)	Comments
Smooth surfaces to aid cleaning	All	Indoor confinement	NH_3	Not available	A smooth floor surface will increase the effectiveness of frequent removal by both flushing and scraping. However, the smooth flooring can create slippery conditions for animals and personnel.
Maintain manure head space	Swine	Indoor confinement w/ liquid manure accumulation beneath flooring	NH_3, H_2S	Not available	Maintenance of at least 12 inches between bottom of slat supports and top of manure. Reduced volatilization by maintaining saturated conditions in the air space above the manure surface.
Flush stalls with low-pH liquid	Swine	Indoor confinement	NH_3	70%	One study reported that flushing swine confinement areas with low pH liquid (one to two times daily) achieved approximately 70% reduction in ammonia emissions.
Increased ventilation	Swine	Indoor confinement	NH_3	Not available	Flow-through partitions and under floor ventilation have been proposed to enhance drying of manure that remains on the flooring in partially or totally enclosed confinement facilities.
Water in manure collection gutters	Dairy	Indoor confinement	NH_3	Not available	Gutter cleaners or gravity gutters are frequently used in confined stall dairy barns. The gutters are usually 16 to 24 inches wide, 12 to 16 inches deep, and flat on the bottom. Keeping at least 2 inches of water in manure collection gutters provides a boundary layer to inhibit diffusion.
Manure Management System					
Manure additives - chemical additives (precipitants, enzymes, etc.)	All	Manure management system Land application	NH_3	Not available	A variety of manure additives (enzymes, plant extracts, urease inhibitors, adsorbents, masking agents) have been used in the industry to inhibit NH_3 formation.

Table 2-9. Potential Control Technologies for Reducing Emissions from AFO Processes (Continued)

Control Technology	Animal Sector	Applicable AFO Processes	Pollutants Controlled	Control Effectiveness [a] (%)	Comments
Manure additives - chemical oxidants (e.g. hydrogen dioxide)	All	Manure management system Land application	NH_3, H_2S, VOC	Not available	Additives inhibit all microbial activity through the use of an antimicrobial agent or change the products of manure decomposition by modifying the indigenous microbial ecosystem.
Manure additives - reducing manure pH w/ amendments (e.g., phosphoric acid)	All	Manure management system Land application	NH_3	Not available	Sophisticated application systems are typically required due to their dangerous and corrosive nature. Although using base-precipitating salts is less expensive and less hazardous than acidifying agents, the reduction in manure slurry pH is more transient, and more frequent applications would be required to maintain a low pH.
Addition of alum or simple acid to litter/manure	Poultry, beef cattle	Indoor confinement	NH_3	Not available	Alum reacts with the moisture in the litter to reduce NH_3 volatilization. Alum also has the additional benefit of tying up excess phosphorus thus preventing potential water quality degradation.
Solid separation	Beef, Dairy, and Swine	Liquid or slurry manure handling	H_2S, VOC	Not available	Reduces the organic loading rate to storage ponds and lagoons. Liquid from solids separation is sent to a storage pond or anaerobic lagoon. Separated solids are stored in piles. Mechanical separators (stationary screens, vibrating screens, presses, or centrifuges) or gravity settling basins may be used for this purpose. Emissions from separation activities are dependent on how frequently solids are removed.
Suppression Techniques					
Confinement Facilities					
Addition of fats or oils to feed	All	Outdoor/Indoor feed handling	PM	Not available	Reduces dust generation and entrainment associated with feed handling and consumption.

Table 2-9. Potential Control Technologies for Reducing Emissions from AFO Processes (Continued)

Control Technology	Animal Sector	Applicable AFO Processes	Pollutants Controlled	Control Effectiveness [a] (%)	Comments
Enclosed feeder delivery system	All	Outdoor/Indoor feed handling	PM	Not available	Reduces dust generation and entrainment from feed handling system.
Pelletized feed	All	Outdoor/Indoor feed handling	PM	Not available	Reduces dust generation and entrainment from feed handling system.
Windbreak walls	All	Indoor confinement	PM (and sorbed gases)	Not available	Windbreak walls at the outlet of the building ventilation system will reduce the velocity of the exhaust air and allow gravity settling of entrained PM (and sorbed gases).
Greenbelts	All	Indoor/Outdoor confinement	PM	Not available	Greenbelt of trees or shrubs in front of building system exhaust points and around drylots reduce air velocity and allow gravity settling of entrained PM (and sorbed gases). Also, there can be some direct adsorption of ammonia by the plants used in the greenbelt.
Slope feedlot to enhance drying	All	Outdoor feedlot	NH_3, H_2S, CH_4, VOC	Not available	By creating a 4-6% grade in the S to SE direction, drying and drainage will be enhanced.
Remove solid manure from feedlots frequently	All	Outdoor feedlot Indoor confinement	NH_3, H_2S, CH_4, VOC	Not available	By removing solid manure from the feedlot at least every 7 days pollutant formation and volatilization is reduced.
Water sprays or sprinklers	All	Outdoor feedlot	PM (and sorbed gases)	Not available	Increased moisture content of manure and confinement surface reduces dust generation and entrainment. Water application may increase the potential for anaerobic conditions.
Spraying vegetable oil	All	Indoor confinement	PM	Not available	Spraying vegetable oil on building interior can suppress entrainment.
Manure Management System					

Table 2-9. Potential Control Technologies for Reducing Emissions from AFO Processes (Continued)

Control Technology	Animal Sector	Applicable AFO Processes	Pollutants Controlled	Control Effectiveness [a] (%)	Comments
Permanent covers (w/o gas collection)	All	Solid manure storage	NH_3, H_2S, PM	Not available	Covers reduce entrainment of PM and volatilization of gaseous compounds. Covers may increase the potential for anaerobic conditions.
Impermeable cover w/o gas collection, followed by rapid incorporation at the land application site	Beef, dairy, poultry, swine	Liquid manure storage and treatment (ponds, tanks, anaerobic lagoons) Land application	NH_3, H_2S	> 80% (NH_3) > 95% (H_2S)	Impermeable covers are commercially available and they are currently being used in AFO industry, but not extensively. However, unless accumulated biogas is collected, leakage will occur due to pressure buildup. Soluble compounds (NH_3 , H_2S) will be suppressed to some degree, but CH_4 and insoluble VOC will be emitted. In a two-cell anaerobic lagoon system, suppressed emissions will volatilize from storage following anaerobic digestion if the storage basin is uncovered. Rapid incorporation must be used to prevent suppressed compounds from being emitted at the land application site.
			Land Application		
Surface application followed by immediate incorporation	Beef, dairy, poultry, swine	Land application	NH_3 , H_2S, VOC	55 - 60% (gaseous compounds)	Rapid incorporation of surface-applied manure into the soil reduces the volatilization of H_2S, NH_3, and VOC. Typically, solid and semi-solid (slurry) manures are applied using tractor-drawn or truck-mounted spreaders. Band spreaders and trailing shoes or pipes/hoses are commonly used to apply semi-solid (slurry) and liquid manures. Incorporation of applied manure into the soil is typically done by plowing or disking.

Table 2-9. Potential Control Technologies for Reducing Emissions from AFO Processes (Continued)

Control Technology	Animal Sector	Applicable AFO Processes	Pollutants Controlled	Control Effectiveness [a] (%)	Comments
Direct injection of liquid manure	Beef (liquids only), dairy, poultry, swine	Land application	NH_3, H_2S, VOC	87 - 98% (NH_3) (reductions of other compounds likely comparable)	Typically, openings (e.g., channels, holes) are made in the earth to accept manure and the openings are covered in a single pass (rather than two separate passes using surface application techniques). Direct injection equipment is commercially available. However, the current level of use in the AFO industry is less than surface application followed by rapid incorporation primarily due to the cost of equipment power requirements.

Table 2-9. Potential Control Technologies for Reducing Emissions from AFO Processes (Continued)

Control Technology	Animal Sector	Applicable AFO Processes	Pollutants Controlled	Control Effectiveness [a] (%)	Comments
Control Techniques					
Confinement Facilities					
Filtration	Dairy, poultry, swine	Indoor confinement	PM (also sorbed VOC)	50 - 60%	Experimental use of filters to reduce PM emissions from housing was reported in the literature. However, the current level of usage in AFO industry is unclear but likely negligible. Filtration can be applied to the building exhaust gases for houses which are mechanically vented or integrated into an internal air recirculation system for houses that are naturally ventilated.
Ionization - electrostatic precipitation - room ionizers	Dairy, poultry, swine	Indoor confinement	PM (also sorbed VOC)	40 - 60%	No farms currently use ionization to reduce PM emissions. However, ionization is a proven technology for reducing PM emissions in other industries and the technology should be transferrable to the AFO industry. Ionization can be applied to the building exhaust gases for houses that are mechanically vented or integrated into an internal air recirculation system for houses that are naturally ventilated.
Ozonation	Poultry, swine	Indoor confinement	All reduced gaseous compounds	15-50%	A strong oxidant that reacts with most organic materials, including organic compounds and microorganisms. Although ozone has been used in treating drinking water, limited work has been conducted in evaluating the use of ozone to oxidize reduced gaseous compounds (ammonia and hydrogen sulfide) from AFOs.

Table 2-9. Potential Control Technologies for Reducing Emissions from AFO Processes (Continued)

Control Technology	Animal Sector	Applicable AFO Processes	Pollutants Controlled	Control Effectiveness [a] (%)	Comments
Wet scrubber	Poultry, swine	Indoor confinement	PM (NH_3, H_2S, soluble VOC)	90% (PM)	Control technique for reducing emissions from confinement housing ventilation exhaust. Typically an enclosed tower (with or without packing material) or wetted pad where housing ventilation exhaust flows counter-current to the flow of water. Pollutants are removed by direct impaction and interception with or diffusion into water droplets.
Biofilter	Dairy, poultry, swine	Indoor confinement	PM, NH_3, H_2S, CH_4, VOC	50 - 80% (NH_3) 80 - 86% (H_2S)	Ventilation system exhaust is passed through a filter bed (e.g., soil, compost, wood chips) in which an established microbial population oxidizes reduced compounds as they pass through to filter bed. There are approximately 13 full-scale biofilters in operation, with more installations expected in the future.
Bioscrubber	Poultry, swine	Indoor confinement	NH_3, H_2S, soluble VOC	89% (NH_3) H_2S	Similar to biofiltration with the exception that the microorganisms are housed in an enclosed packed tower with water circulated countercurrent to the incoming building air, instead of in a filter bed. As contaminated air is passed through the scrubber, water-soluble compounds (NH_3, H_2S) are absorbed by the water and oxidized microbially.
Chemical (acid) scrubber	Poultry, swine	Indoor confinement	PM, NH_3	Unknown	Similar to wet scrubbing with the addition of chemicals to absorb gaseous compounds.
Washing wall (wet pad)	Poultry, swine	Indoor confinement	PM, NH_3	53% (NH_3)	A water curtain intended to remove PM as the building air passes through it, using the same removal mechanism (i.e., impaction) as a wet scrubber.
Manure Management System					

Table 2-9. Potential Control Technologies for Reducing Emissions from AFO Processes (Continued)

Control Technology	Animal Sector	Applicable AFO Processes	Pollutants Controlled	Control Effectiveness [a] (%)	Comments
Biocovers	Dairy, poultry, swine	Manure management system (ponds, tanks, anaerobic lagoons)	NH_3, H_2S, CH_4, VOC	48-89% (NH_3) 62-98% (H_2S) 64-90% (VOC) (reductions of CH_4 likely comparable)	Biocovers are gas-permeable membranes. Microbes that grow within the permeations oxidize reduced compounds as they pass through to cover. Biocovers are commercially available and are being evaluated by the AFO industry (at least one full-scale installation).

Table 2-9. Potential Control Technologies for Reducing Emissions from AFO Processes (Continued)

Control Technology	Animal Sector	Applicable AFO Processes	Pollutants Controlled	Control Effectiveness [a] (%)	Comments
Capture and combustion of biogas from anaerobic digesters and covered anaerobic lagoons	Dairy, poultry, swine	Liquid or slurry manure management system	NH_3, H_2S CH_4, VOC	90% (H_2S, CH_4, VOC)[c] Not available (NH_3)	Anaerobic digesters and covered anaerobic lagoons with biogas recovery are in operation at about 40 commercial scale dairy and swine operations in the U.S. These systems include: •Covered ambient temperature anaerobic lagoons •Mesophillic (heated) digesters •Thermophillic (heated) digesters •Fixed-film digesters These systems have the potential to offset the costs of control by recovering the energy contained in the biogas (e.g., for the production of electricity and hot water). Combustion releases carbon dioxide, a greenhouse gas, but emissions of methane (a far more persistent greenhouse gas) are nearly eliminated. Uncovered storage following anaerobic digestion will emit NH_3 and H_2S.

[a] The percent reductions are applicable only to the emissions that are generated by the applicable AFO process, not the total emissions from all AFO processes. For example, biofilters have been shown to reduce NH_3 emissions from confinement houses by 50 to 80 percent, but emissions from houses vary depending on the type of manure management system.

[b] Although two articles were identified that described reduction of NH_3 emissions (10 - 17%) achieved by optimizing protein digestion, the reductions realized by diet modification may be only marginal. Typical levels of dietary protein do not significantly exceed nutritional requirements and the inherent biological inefficiency of protein utilization in animals limits the potential reduction of excreted nitrogen. The potential magnitude and significance of H_2S reductions remains unclear.

[c] No emission reduction performance data are available for capture and combustion of biogas from manure storage and treatment processes. However, the control efficiency of the gas collection system and combustion device (98% destruction) for reduced gaseous compounds was estimated to be 90 percent (based on engineering judgment).

Appendix A

Listing of Chemical Substances Identified in and Around Livestock Manure

Appendix A.

Listing of Chemical Substances Identified In and Around Livestock Manure (Adapted from O'Neill and Phillips, 1992)

Group	Compound Name	Note	Compound Name	Note
Carboxylic acids	formic acid	a	oenanthic acid	a
	acetic acid	a	caprylic acid	a
	propionic acid	a	pelargonic acid	a
	n-butyric acid	a	capric acid	a
	i-butyric acid	a	hendecanoic acid	a
	pentanoic acid	a	lauric acid	a
	3-methylbutanoic acid	a	tredecanoic acid	a
	2-methylbutanoic acid	a	myristic acid	a
	2-methly-2-butenoic acid	a	benzoic acid	a
	hexanoic acid	a	penylacetic acid	a
	4-methylpentanoic acid	a	3-phenylpropionic acid	a
	2-methlypentanoic acid	a		
Alcohols	methanol	a, b	l-heptanol	a
	ethanol	a	iso-heptanol	a
	n-propyl alcohol	a	3-octanol	a
	i-propyl alcohol	a	2-ethylhexanol	a
	n-butyl alcohol	a	2-methoxyethanol	a
	sec-butyl alcohol	a	2-ethoxy-l-propanol	a
	isobutyl alcohol	a	2,3-butanediol	a
	pentanol	a	benzyl alcohol	a
	i-pentanol	a	α-methlbenzyl	a
	l-hexanol	a	4-methylcyclohexanol	a
	hex-3-ene-1-ol	a	2-penylethanol	a
	2-methy-2-pentanol	a		
Phenolics	phenol	a, b	p-ethylphenol	a
	p-cresol	a, b	m-ethylphenol	a
	m-cresol	a, b	o-ethylphenol	a

Appendix A.

Listing of Chemical Substances Identified In and Around Livestock Manure (Adapted from O'Neill and Phillips 1992) (Continued)

Group	Compound Name	Note	Compound Name	Note
Phenolics (Cont.)	o-cresol	a, b	2,6-dimethyl phenol	a
	p-methoxyphenol	a	3,4-dimethylphenol	a
	o-methoxyphenol	a	3-hydroxy-2-methyl-4-pyrone	a
Aldehydes	formaldehyde	a, b	2-nonenal	a
	acedtaldehyde	a, b	2,4-nonadienal	a
	propionaldehyde	a, b	capraldehyde	a
	acrolein	a, b	2,4-decadienal	a
	butyraldehyde	a	benzaldehyde	a
	iso-butyraldehyde	a	acetone	
	crotonaldehyde	a	diacetyl	a
	valeraldehyde	a	(2-)butanone	a, b
	iso-valeraldehyde	a	acetoin	a
	2-pentenal	a	3-pentanone	a
	caproaldehyde	a	cyclopentanone	a
	2-hexenal	a	2-methyl	a
	oenanthaldehyde	a	2-octanone	a
	2-heptenal	a	amylvinylketone	a
	2,3-heptadienal	a	acetophenone	a, b
	caprylaldehyde	a	pelargonaldehyde	a
Esters	methylformate	a	i-propylacetate	a
	methylacetate	a	butylacetate	a
	elthylformate	a	i-butylacetate	a
	ethyl acetate	a	i-propylpropionate	a
	propylacetate	a		
Nitrogen heterocycles	indole	a	(2)-methylpyrazine	a
	skatole	a	methylpyrazine	a
	pyridine	a	trimethylpyrazine	a

Appendix A.

Listing of Chemical Substances Identified In and Around Livestock Manure (Adapted from O'Neill and Phillips 1992) (Continued)

Group	Compound Name	Note	Compound Name	Note
Nitrogen heterocycles (Cont.)	3-aminopyridine	a	tetramethylpyrazine	a
Amines	methylamine	a	pentylamine	a
	ethylamine	a	trimethylamine	a
	n-propylamine	a	triethylamine	a, b
	i-propylamine	a		
Sulphides	carbon disulphinde	a, b	methylpropyldisulphide	a
	carbonylsulphide	a, b	propylporop-1-enyl disulphide	a
	dimethylsulphide	a	diphenylsulphide	a
	diethylsulphide	a	3,5-dimethyl-1,2,4- trithiolane	a
	dimethyldisulphide	a	3-methyl-5-propyl-1,2,4-trithiolane0	a
	dimethltrisulphide	a	3,6-dimethyltetra-thiane	a
	diethyldisulphide	a	2,6-dimethylthi-3-inc-carbonaldehyde	a
	dipropyldisulphide	a		
Thiols (mercaptans)	methanethiol	a	butanethiol	a
	ethanethiol	a	2-butene-1-thiol	a
	propanethiol	a	benzenethiol	a
	2-propanethiol	a	α-toluenethiol	a
	2-propene-1-thiol	a		
Other unclassified compounds	sulphur dioxide		indane	a
	methane		napththalene	a, b
	pentane	a	methylnaphthalene	a
	2-methylpentane	a	chloroform	a, b
	hexane	a, b	tetrachloroethane	a
	hexene	a	hydrazine	a, b
	heptane	a	2-methylfuran	a

Appendix A.

Listing of Chemical Substances Identified In and Around Livestock Manure (Adapted from O'Neill and Phillips 1992) (Continued)

Group	Compound Name	Note	Compound Name	Note
Other unclassified compounds (Cont.)	octane	a	2-pentylfuran	a
	octene	a	2-methylthiophene	a
	undecene	a	2,4-dimethylthiophene	a
	dodecane	a	diethylether	a
	benzene	a, b	limonene	a
	toluene	a, b	ocimene	a
	xylene	a, b		

[a]The compound is classified as a volatile organic compound by EPA.
[b]The compound is classified as a hazardous air pollutant by EPA.